Building Information Modeling and Structural Analysis in the Knowledge Path of a Historical Construction

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Abstract. In the field of historical buildings, the development of the knowledge of the structural characteristics is essential to assess the structural risks of a construction. The preservation of memory, the respect for heritage principles and the interdisciplinarity of the subject make analysis more complex. An exhaustive knowledge path of historical constructions goes through a deep analysis of all interventions carried out, the constructive evolution, the geometric and mechanical characteristics of the building, the structural forces that have already act in the past and in the current configuration, the built environment and the atmospheric environmental factors, the maintenance interventions, etc. Using exhaustive methodologies capable of satisfying the needs of designers is important due to the large number of factors influencing such a study and the difficulty of obtaining and collecting information. The objective of this work is to investigate existing and proven options of methodologies in order to apply them to the field of built heritage constructions. The main aim is to achieve an overall study of the historical building characteristics. Defining an interpretive model allows both a qualitative interpretation of the structural performance and a structural analysis for a quantitative evaluation. In the paper, a multidisciplinary analysis is proposed adopting two proven methodologies: the knowledge path and Building Information Modeling (BIM). The chosen case study is the Troop Barracks in the old fortress located in Anhatomirim Island (SC), Brazil. This aims to show how the proposed methodologies can be adapted to historical building in structural masonry and wooden horizontal elements.

Keywords: Knowledge path · Historic-BIM · Structural analysis
Risk assessment · ELARCH

1 Introduction

The development of the knowledge of the structural characteristics of a historical building is crucial for any kind of analysis aimed at assessing the structural risk. In the case of masonry buildings, with horizontal wooden elements, the analysis of constructive evolution has primary importance in understanding the structural behavior. This type of analysis allows developing an appropriate approach for the structural

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knowledge of an existing building, with peculiar historical value. The case study chosen is the "*Quartel da Tropa*" (literally translatable as a troop barracks) belonging to the fortress of the Anhatomirim Island, Santa Catarina, Brazil.

The scientific contribution and originality of this paper are to propose a multidisciplinary approach analysis for the structural understanding of historical buildings through the presentation of the preliminary results of a more extensive and complete research. Two proven methodologies have been merged as a unique research tool: the Building Information Modeling (BIM) and the knowledge pathway for evaluating and reducing structural risk assessment of cultural heritage [2]. Furthermore, the combination of those methodologies allows a better understanding of the structural risk for cultural built heritage. The basis of this approach is the integration of information relating to different construction phases, according to the evaluation and classification of the interventions made during the life of the building.

2 Scientific Review

The bibliographic review chapter focuses on architectural heritage issues with particular interest in masonry and wooden construction, which are a usual frequent model of historic construction both in Brazil and in Europe. In order to reach an adequate level of knowledge of this type of building can be useful to identify methodologies that accompany the professional during the analysis of the constructive evolution of a historical building, in relation to the evaluation of the physical, mechanical and geometric characteristics of the construction. The knowledge path is crucial for the decision-making phase for restoration and rehabilitation proposals of historic buildings. The most appropriate methodology found for the collection of information for historical buildings is Building Information Modeling (BIM).

2.1 Heritage Buildings

As a theoretical basis for this research, the conservation methodology for historical constructions proposed by the International Council on Monuments and Sites [3] is summarized here. It consists of four phases, divided into several stages: (1) data acquisition, through historical survey, geometrical survey of the structure, in-situ investigation campaign with laboratory experiments and structure monitoring; (2) structural behavior, through a structural schematic and creation of a model, definition of the characteristics of the materials and actions in the structure; (3) diagnostic and safety plan, through historical-critical, qualitative, quantitative and experimental analysis; (4) proposals for restoration work involving masonry structures, wood, iron and steel, and reinforced concrete.

The scientific method used in these phases is to blend into hypotheses deriving from the structural model, experimental results obtained from historical-critical analysis, inspection of as-built conditions, and monitoring of the structure [4].

2.2 Masonry and Wooden Historical Building: Structure and Acting Forces

A fundamental step to understand the behaviour of a historical building in masonry and wood is structural analysis in each construction phase [5]. Such type of buildings can be briefly described by vertical elements such as walls, arches or pillars, and horizontal elements, slabs, roofs or vaults. The structural behavior of these constructions is strongly influenced by the quality of the connections between vertical and horizontal structural elements. An adequate reinforcing intervention on horizontal wooden elements cannot ignore the quality of the connections between the vertical and the horizontal structural elements [6].

In the case of masonry buildings, horizontal actions such as earthquake and wind are risky loading conditions [7]. In order to define these loads, the evaluation process suggested by the regulations of the country in which the construction is located can be adopted. Another important condition that can affect an existing building can be the contribution of the loads and the effects due to the presence of the soil in relation to the structure. A horizontal action relevant to a masonry building may arise when the structure is in direct contact with the ground, for example, in the case of having a part of the construction buried by one or more sides.

The lateral actions directly affect the transversal walls, perpendicular to the direction of the force, which transfer the strain to the lower slabs and to the foundation structures [8]. The horizontal structural elements are in-plane stressed and the stresses are transferred to the foundation through the opposition of the structural walls. The presence of a horizontal element, also referred to as a diaphragm, with good wall-to-wall and wall-to-diaphragm connections, can improve the overall ability to withstand horizontal actions [9].

2.3 Building Information Modeling (BIM) Applied to Building Heritage

The use of the BIM method in newly-built projects is now a recurring practice in the construction world [10]. Finding examples of BIM applications in the world of restoration of historic buildings is not common. This is mainly due to the effort required in the digital conversion of the collected data. It is often incomplete, fragmented and outdated, not providing the basics for a broad and complete modeling [11].

In this paper, the references that deal with the BIM method together with the structural analysis in the field of historic buildings have been reviewed. An example is Dore's research [12], where the bases for structural simulations and building conservation analyzes are presented and named as Historic Building Information Model (HBIM). In the previous work [12], the architectural rules and grammars are exploited to systematically model parts of structures in order to accelerate and automate parts of the process. The resulting HBIM can be used to automatically produce conservation documentation and structural analysis of historical building, as well as their visualization [12]. However, in recent scientific literature, many researches presenting methodologies have been found [12–16]. They integrate multidisciplinary processes of interaction between information, documentation, management and knowledge of historical buildings [12–16]. Nevertheless, those methodologies are partial and do not include structural analysis. Only a combination of those methodologies can lead to a multidisciplinary approach to improve the knowledge path of historical buildings and to increase the Level of Development (LoD), that represents both the level of detail of the geometric definition and the level of information associated with it [13].

3 Methodology

The approach proposed in this paper is based on the methodologies cited in the previous chapter. According to the proposed scientific review, the knowledge path proposed in the "Guidelines for Assessment of Seismic Risk of Cultural Heritage Assessment" [2] together with the BIM methodology [14] have proved compatibility in the field of historic buildings. One of the main goals can be to create a unique digital model. It provides the most significant information and allows for continuous updating of its information, supporting the historical building management. In fact, knowledge of a historical building is a prerequisite for an adequate structural risk assessment, including a possible decision-making phase. The development of multidisciplinary analysis begins with the collection of historical, technical and geometric data, associated with BIM objects for each stage. These data can be obtained through different techniques and experiments, *in situ* or in laboratory, destructive or non-destructive, with the aim of obtaining information on the properties of the materials [15].

Following the constructive identification of the building, the initial phase of this process consists of the historical-critical analysis of the construction and its geometric survey. These data, critically elaborated, are the basis for the creation of the BIM architectural model, which can also be enriched by the information obtained in the following phases: the characterization of the materials, the material survey, the constructive system and the state of conservation of the building, combined with the evaluation of the geotechnical context.

In the absence of experimental data on the material characteristics, the chosen parameters have been selected from a proven source such is the Italian code, *Circolare 617* (2009) [1]. It suggests some values - taken from the experience of scientific literature - to characterize a masonry construction in the absence of experimental campaign results. Those parameters are: average compressive and shear strength of masonry (f_m = 1,4 N/mm^2, τ_0 = 0,026 N/mm^2), longitudinal and tangential Young's Modulus (E = 870 N/mm^2, G = 290 N/mm^2), Poisson's ratio (ν = 0,25), average specific weight of masonry (w = 19 N/mm^2). Concerning the timber elements, an experimental campaign reveals the existence of different wooden species in the construction [16] with a prevalence of *Peroba Rosa* ("*Aspidosperma pirycollum*"). For this reason and for the purpose of the preliminary analysis of this research, all wooden structures are assumed with the same characteristics [17] of the latter species.

Once the previous steps can be considered as concluded, depending on the level of knowledge required, with the relevant information that is deemed necessary in the architectural model, the BIM structural model can be created. As a final step, one can develop both quantitative and qualitative structural analyses through specific calculation tools and software, with the aim of achieving adequate and consistent results. As already stated, the path of knowledge of an architectural heritage structure should reach a high level of information and data. In the path of knowledge of a historical building that has undergone several structural changes during its life, one of the most interesting challenges is to understand the constructive evolution of the building, from its as-design to the as-built states. This information may come from existing research, carried out by other professionals and researchers, or may be part of the research work of the designer who is pursuing the path of knowledge of a building heritage.

4 Results

The chapter of the obtained results aims to show how the proposed multidisciplinary approach can be adapted to any type of masonry and wooden historical building. The chosen building is the "*Quartel da Tropa*" (literally troop barracks) belonging to the Santa Cruz Fortress group of the Anhatomirim Island (Santa Catarina), Brazil. This selected building had already a number of relevant data and survey to be used in the research. The acquired information will be useful to improve its level of knowledge.

4.1 Study Case: "*Quartel Da Tropa*"

The "*Quartel da Tropa*" on the Anhatomirim Island, Brazil, is a typical 18th-century building with masonry vertical elements and wooden horizontal elements, like slab and roof. Designed by the Portuguese military engineer Brigadier José da Silva Paes, the building was one of the vertexes of the triangular defense system, formed together with the Fortresses of *São José da Ponta Grossa* and of *Santo Antônio de Ratones*.

According to historical research related to this building, the constructive evolutions in four main stages can be reconstructed and represented in the BIM model [18]: the as-designed project of 1747 (see Fig. 1a), insertion of the central masonry slope-shaped element of 1760 (see Fig. 1b), insertion of the buttresses of 1843 (see Fig. 1c), restoration interventions of 1970 (see Fig. 1d). The wooden horizontal structural

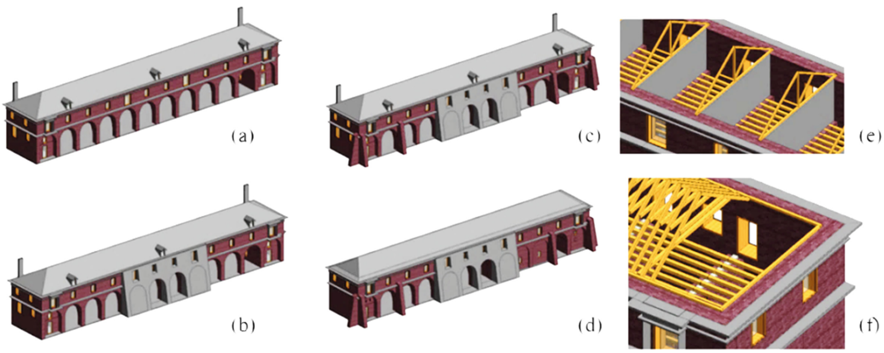

Fig. 1. Constructive evolution of the "*Quartel da Tropa*": as-designed project (a), central masonry slope-shaped element (b), insertion of the buttresses (c), as-built project (d), roof structure before (e) and after (f) the restoration of 1970

elements have undergone profound modification in the restoration of 1970 [18], according to a trend also found in other architectural heritage sites in Brazil [19]. The structure of the roof that was simple trusses, with king post and struts (see Fig. 1e) was replaced with trusses with collar tie beam (see Fig. 1e). In the same restoration of 1970, the beams of the wooden slabs, which were fixed in the masonry walls, were substituted by simply supported beams resting on new reinforced concrete beams, applied on the masonry arches (see Fig. 1f).

4.2 Qualitative Interpretation of the Structural Performance

In order to understand structural changes introduced by replacing the structural systems of horizontal wooden elements, both in the slabs as well as in the roof (see Fig. 2a and b), some simplified linear analyses using FTOOL® structural calculation software were conducted. The normative basis for the evaluation of the horizontal actions is the Brazilian codes for wind, NBR 6123-1988 [20], and earthquake, NBR 15421-2006 [21]. The different load combinations regarding wind [20] and seismic [21] actions were obtained. The higher action is the wind load, 4.40 kN/m upwards. The as-built structure, with simple collar ties, has undergone greater bending moment and shear stresses (Table 1). It causes a considerable increase in displacement (See Fig. 2b) in the roller support, with horizontal displacement allowed. This behavior creates a higher risk of out-of-plane overturning in the transversal masonry walls.

Similarly, wooden beams of horizontal diaphragms were analyzed by calculating their own weights and stresses from experimental building campaigns [16] and Brazilian national standard [22, 23]. The obtained load of 2.43 kN/m causes higher stresses and deformations in relation to the different types of structures before (fixed supported beams, see Fig. 2c) and after (pinned supported beams see Fig. 2d) to the restoration work of 1970.

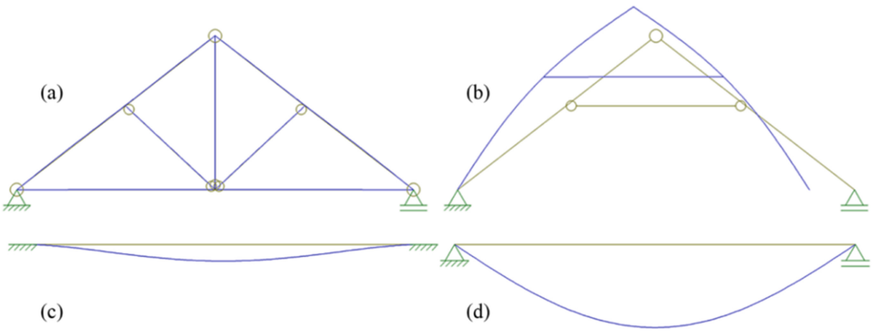

Fig. 2. Constructive evolution of the wooden structure: roof structure before (a) and after (b) the restoration of 1970, slab wooden beam before (c) and after (d) the restoration of 1970

Table 1. Comparison of strain and stresses of structural wooden elements before and after the restoration of 1970

	Trusses		Beams	
	King post and struts	Collar tie	Fixed supported	Pinned supported
Normal Stress	24.1 kN	19.2 kN	–	–
Shear Stress	8.2 kN	15.0 kN	7.9 kN	7.9 kN
Bending Moment	4.3 kN m	24.4 kN m	8.60 kN m	12.80 kN m
	Roller support displacement		Middle span deformation	
	0.28 mm	133.10 mm	0.85 mm	4.24 mm

4.3 Structural Analysis for a Quantitative Evaluation of the Construction

The creation of the BIM structural model, in this research designed in Revit®, allows the designer to export the file to other structural analysis software. In this work, Finite Element Method (FEM) software was chosen: Robot Structural Analysis®. This allows developing quantitative structural analyses in order to obtain a comprehensive understanding of the historical structure. An example of structural analysis can be the modal analysis. In the case of complex constructions, it can describe global structural behaviour, even in terms of stiffness in each of the main directions. In this perspective, modal analyses were developed, modeling the vertical masonry elements in each of the 4 main phases of the constructive structural evolution. The aim of this analysis is to study the variation of stiffness in each direction. In the calculation of the first 100 vibrational modes of the as-built model, a description in terms of percentage mass was obtained. Different modal shapes have been found in the two different directions, with participation mass greater than 5%, meaning that the structure does not perform as a box-behaviour. According to the previous results, the analysis of the structural modal shape forms in every direction could be evaluated even for a static approach. It can represent the basis for non-linear analysis in future research and future work on the historical building analyzed (Table 2).

Table 2. Evolution of the dynamics parameters according the constructive evolution of "*Quartel da Tropa*"

	Transversal direction (X)			Longitudinal direction (Y)		
	As-designed	Central element	Buttresses	As-designed	Central element	Buttresses
T_1 (s)	0.45	0.44	0.38	0.58	0.57	0.56
f_1 (Hz)	2.20	2.26	2.62	1.71	1.74	1.78
ω_1 (rad/s)	1.40	1.44	1.67	1.09	1.11	1.13
k_1 (kN/m)	6402.03	7531.86	10601.59	1813.89	2195.75	2050.66
m (kN)	32609.31	36386.43	38107.85	15306.81	17894.85	15978.62
Stiffness increment	–	18%	56%	–	21%	11%

Below, the modal shapes obtained from the modal analysis of the first vibrational mode in both directions with respect to the constructive evolution are shown (see Fig. 3). The insertions of the central masonry slope-shaped element and of the buttresses had a positive contribution, stiffening the structure in both directions.

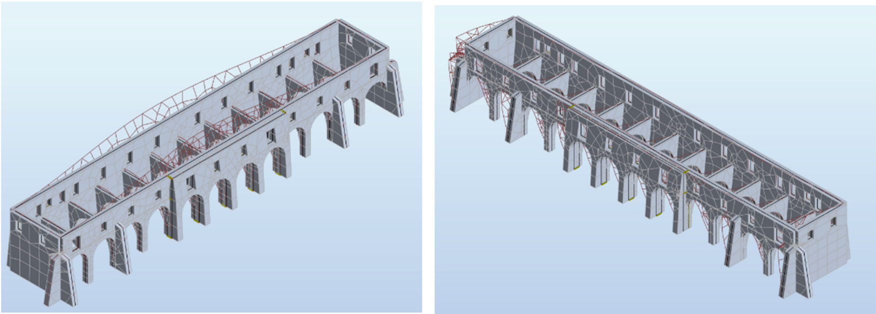

Fig. 3. First modal shape of the as-built model e in the transversal direction (left) and in the longitudinal direction (right)

5 Conclusions

In this paper, a multidisciplinary approach, which can be applied to historical constructions, is proposed. The methodologies cited in the bibliographic references show how they can be merged in order to create the basis for a comprehensive interpretation of a historical structure. At the same time, they demonstrate how much research can still be done involving a multidisciplinary approach. The historical-critical analysis allows understanding the constructive evolution of a structure, facilitating its understanding process. The results obtained show the structural modifications caused by the different restorations along the time. The interventions for masonry structures, unlike the horizontal wood structures, had a positive impact in relation to the global stiffness of the building. The structural analysis approach and the Building Information Modeling method proved to be fundamental tools in the path of knowledge of a historic building.

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